FR21998-23

AD-A283 459

15 May, 1994

# FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS
**Technical Progress Report**

**Daniel P. DeLuca**
**Principal Investigator**

**Charles Annis**
**Program Manager**

UNITED TECHNOLOGIES
PRATT & WHITNEY
P.O. Box 109600
West Palm Beach, FL 33410-9600
(407)796-6565
Government Engines and Space Propulsion

15 May, 1994

Period of performance
16 February 1994 through 15 May 1994

Contract N00014-91-C-0124



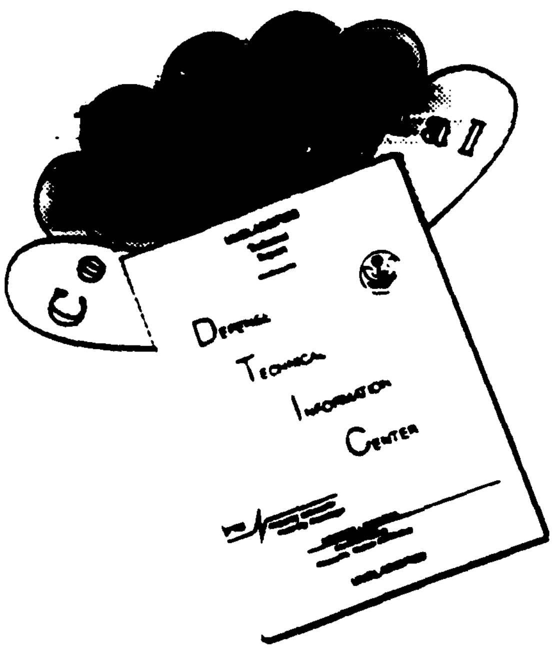
Prepared for:
Dr. A. K. Vasudevan, Scientific Officer
Code 1222





**Office of Naval Research**
**Department of the Navy**
800 N. Quincy Street
Arlington, Va 22217-5000

# DISCLAIMER NOTICE



**THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF COLOR PAGES WHICH DO NOT REPRODUCE LEGIBLY ON BLACK AND WHITE MICROFICHE.**

# I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

## Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200+Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete $\gamma'$ solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.



1 Chen O. Y., 1985, "Crystallographic Fatigue Crack Propagation in Single Crystal Ni-Base Superalloy" Dissertation, The University of Connecticut

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are $\gamma'$ strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal $\gamma'$ precipitates in a $\gamma$ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

**Single Crystal Fatigue**

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the <001> crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical

crystallographic propagation. At 982C, propagation is almost entirely non-crystallographic, similar to transgranular propagation in a polycrystal.

**Damage Catalogue**

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at no cost. The work is organized into four tasks, which are described in the following paragraphs.

## II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

**Task 100 - Micromechanical Characterization**

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

**Task 200 - Analytical Parameter Development**

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

**Task 300 - Probabilistic Modeling**

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the

Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

**Task 400 - Reporting**

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

## III. Technical Progress

We are currently examining the conditions that cause macroscopic (111) fracture to become operative and the various limits under which global (111) propagation becomes an available fracture mode. The fundamental elements of single crystal deformation provide a basis for understanding the cyclic behavior of PWA 1480 and PWA 1484.

Single crystals deform by shearing along (111) crystallographic planes, sometimes referred to as "octahedral" planes. This shearing occurs in the <110> family of directions (Figures 1- 2). The direction of load application with respect to crystal orientation determines the resolved shear stress for each of the *(111)/<110> slip plane/direction sets constituting particular slip systems.* As applied load is increased, additional slip systems become operative, making it possible for multiple slip systems to be operative simultaneously. An operative slip system is one where the resolved shear stress is sufficiently high to cause slip. This shear yield stress ($\tau_C$) is also referred to as the materials critical resolved shear stress (CRSS). At a given applied load, more than one slip system may see resolved shear stresses in excess of $\tau_C$ (dependent upon orientation). Only the <123> orientation permits a single slip condition (only one slip system operative) to occur making it a useful orientation for study purposes.

The mechanisms of crystallographic fatigue crack initiation and fatigue crack propagation on a single macroscopic (111) plane are of critical importance to a mechanistically based life prediction system. An example of a "global" octahedral slip/initiation and the conditions which produced it are given in the following discussion.

If the applied stress is sufficiently low, (such that only one slip system is operative) a global slip plane can develop. This condition is shown in Figure 3, a photograph of a slip band observed in a smooth ($K_t$=1), <001> oriented PWA1480 high cycle fatigue (HCF) specimen tested at 20Hz, 26C, R=0.5, in high pressure hydrogen. The global slip band was observed on the surface after the specimen was retired at 10,000,000 cycles.

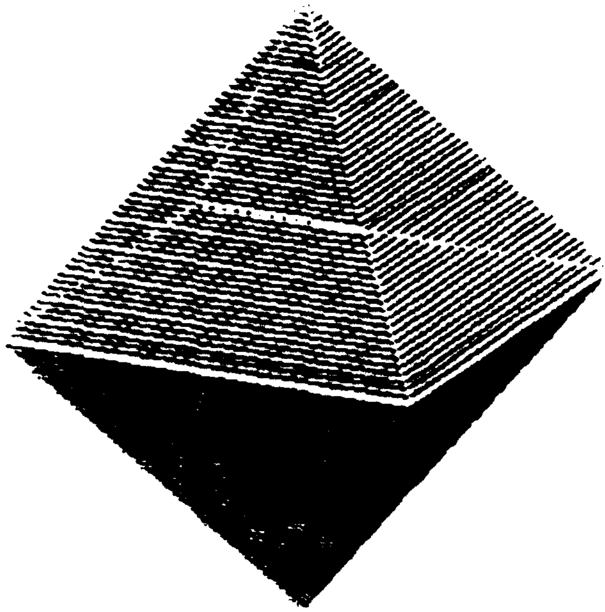


Figure 1. The octahedron described by eight (111) planes.

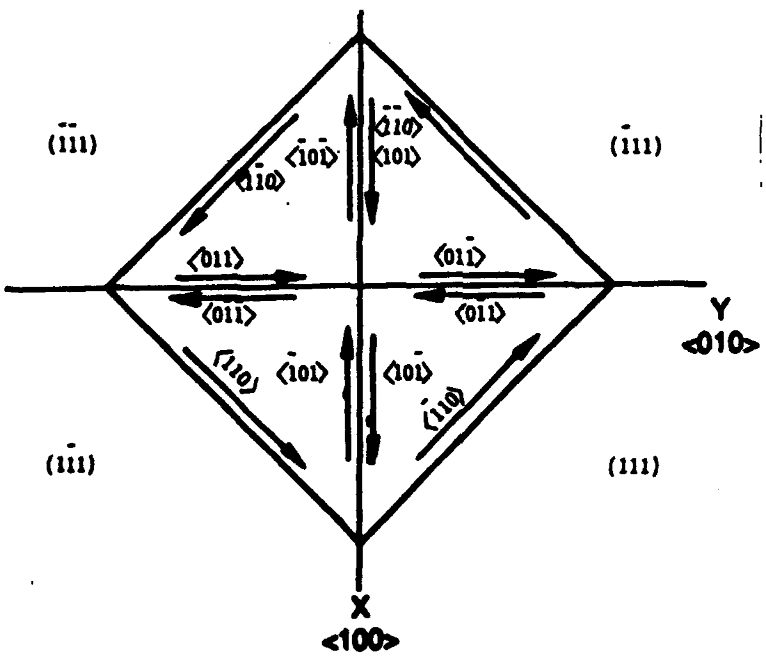



Figure 2. The octahedron viewed from the positive Z axis showing the 12 possible (111)/<110> slip systems.

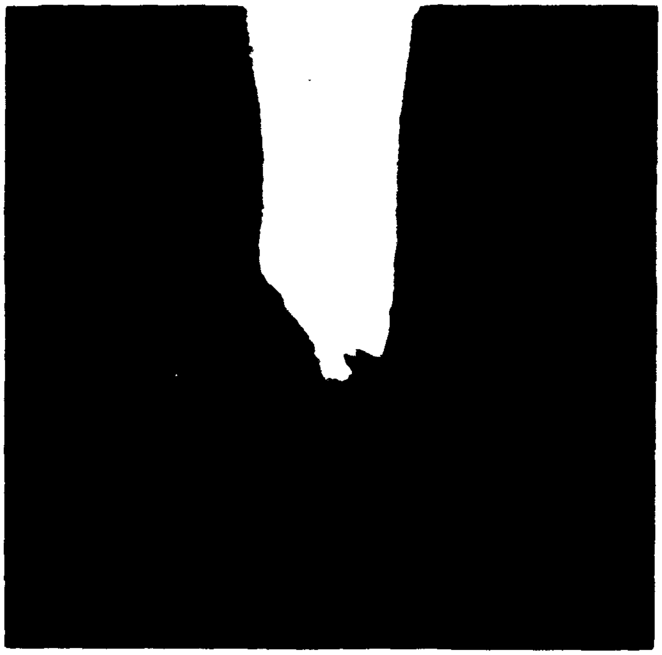


Figure 3. A photograph of a slip band observed in a PWA 1480 HCF test specimen gage section. 5X

Global octahedral failure is the result of strain localization on a single slip system. The deformation preceding fracture is non-homogeneous, planar in nature, and occurs in localized intense or "persistent" slip bands. An example is shown in Figure 4.

Cyclic stressing produces alternating slip reversals that progress to slip band extrusion. Surface crack initiation occurs at these extrusion/intrusions aided in air as an oxidation mechanism precludes slip reversal. A single slip system is able to advance a crack under these circumstances. Our observations suggest that a critical slip displacement is reached before fracture can occur. A higher magnification view (Figure 5) of the specimen shown in Figure 3 reveals a 0.002" crack forming along the persistent slip band at the specimens surface.

Octahedral cracks also initiate sub surface, usually at some point source intrinsic material quality (IMQ) defect. Common IMQ defects in PWA 1480 and PWA 1484 (the subject of previous reports) are carbides, microporosity and eutectic $\gamma - \gamma'$.

The near surface crack shown in Figure 6 initiated at a carbide and is propagating along a (111) plane. The crack was observed by serial sectioning through a PWA 1422 turbine blade attachment test. The condition, octahedral initiation, is thought to be associated with bearing load induced shear stress resolving on favorably oriented (111) slip systems.

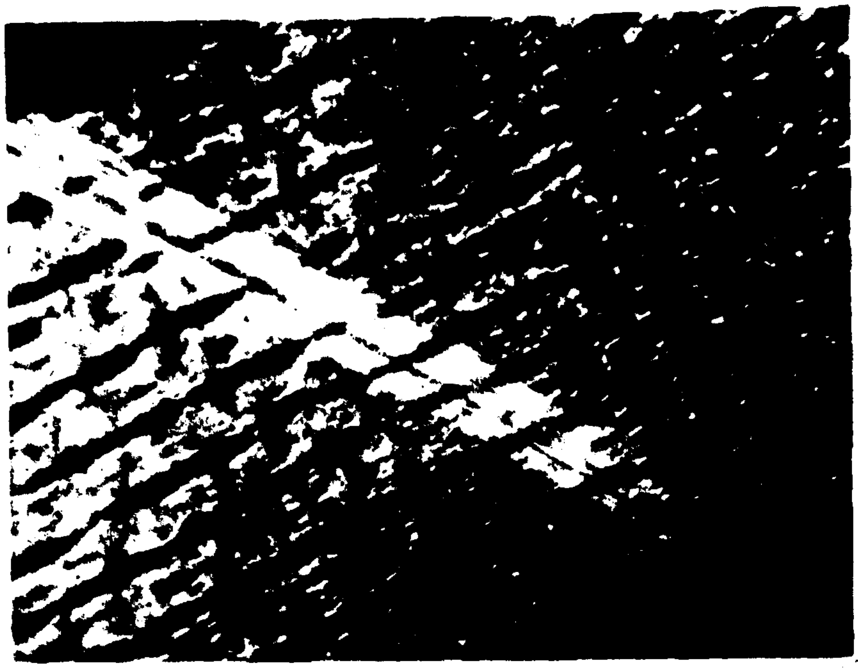


Figure 4: An intense or persistent slip band viewed metallographically and enhanced by polarized light (from Figure 3). Persistent slip bands evolve as initial precipitate shearing by dislocations compromises the order in the γ' superlattice. This creates preferential avenues for further dislocation penetration through the weakened superlattice. 40X

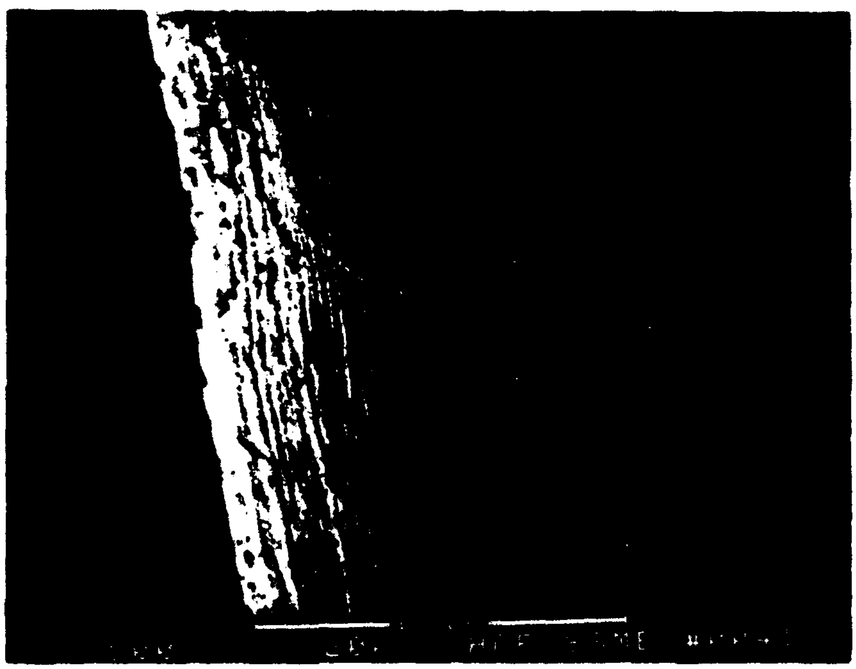


Figure 5. A 0.002" crack forming along a persistent slip band. The amount of slip displacement can be seen silhouetted at the specimen surface.

A second example of a subsurface octahedral fatigue crack is shown in Figure 7. The crack initiated at an IMQ defect (eutectic $\gamma$ - $\gamma'$) in PWA 1484 at 1100F, R=0.1, 136 ksi, 20Hz after 1360000 cycles and propagated in a vacuum.

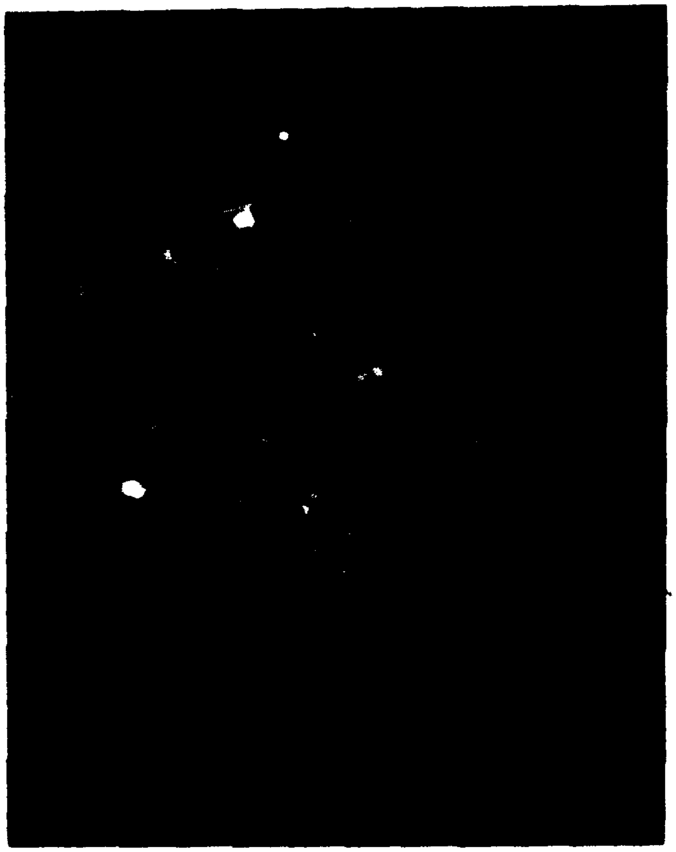


Figure 6. A subsurface fatigue crack initiating at a carbide in PWA 1422 and propagating along octahedral planes. 320X

Chen (1) concluded that in a vacuum, there is no clear distinction between crystallographic crack initiation and propagation processes. He suggests that initiation is by material displacement and transport by a cross-slip/extrusion mechanism requiring at least two operative slip systems to transport extruded material away from the crack tip. Slip occurs out of the fracture plane and lateral to the advancing crack front on intersecting slip systems (shown schematically in Figure 8).

A detailed study of the fracture shown in Figure 7 shows that multiple <110> family slip directions on the global (111) fracture plane are operative. Of particular interest is the presence of slip lateral to the direction of propagation

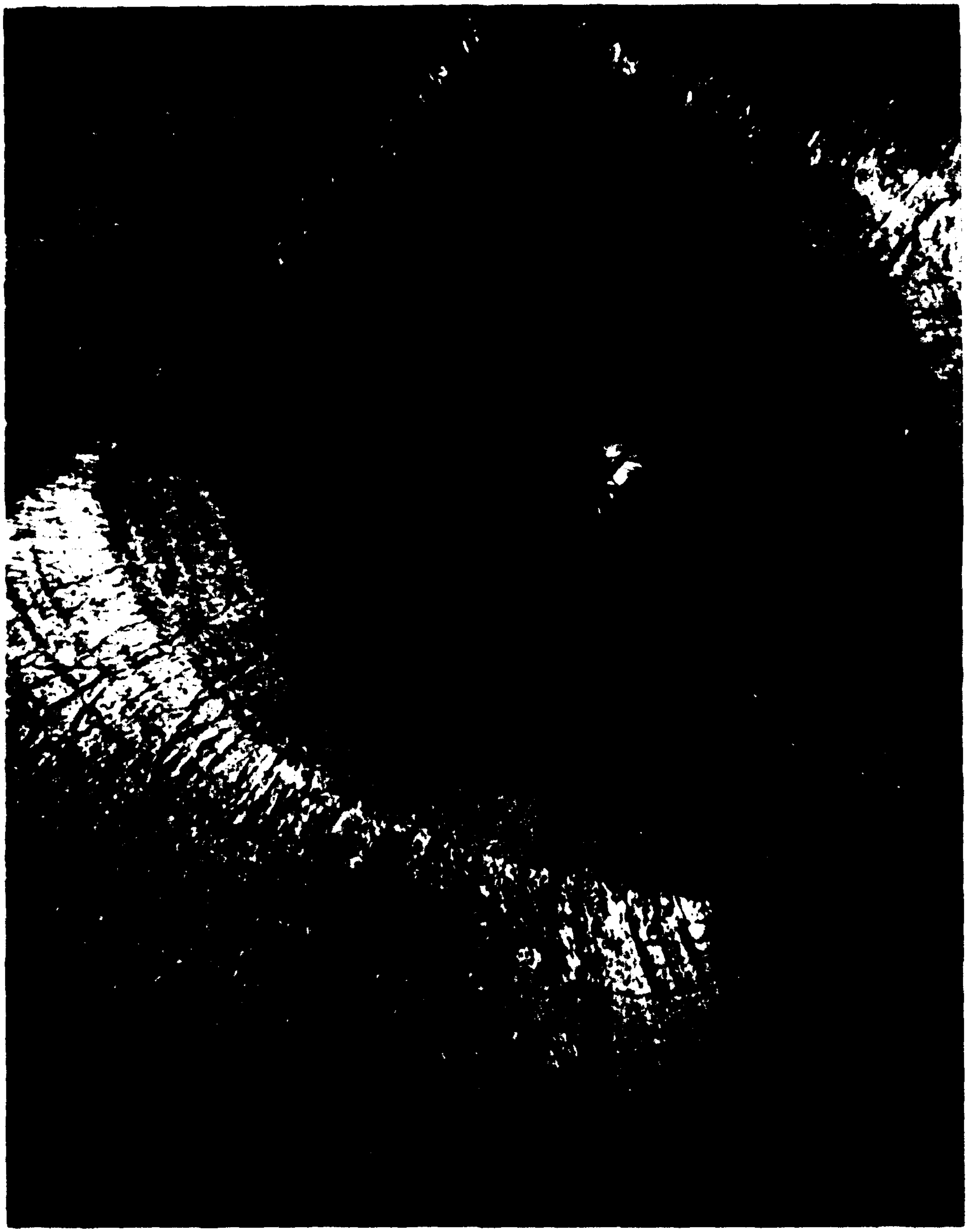


Figure 7. A (111) fracture surface in PWA 1484. The point source defect is eutectic $\gamma$ - $\gamma'$. The hexagonal crack front results from three <110> slip directions being operative. The <110> directions are superimposed. (120X)

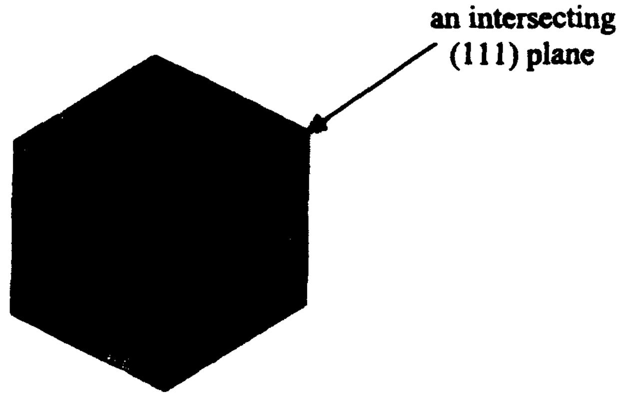



Figure 8. Fine secondary cracks parallel to the <110> slip directions visible in previous figure indicate cross slip on (111) planes (shown schematically) intersecting the fracture plane from beneath.

Figure 9. Cyclic lateral translation of material at the crack tip appears to be producing fine striations on the fracture surface <u>lateral</u> to the direction (112) of crack advance. (500X)

| REPORT DOCUMENTATION PAGE | 1. REPORT NO. FR2198--23 | 2. | 3. Recipient's Accession No. |
|---|---|---|---|

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS<br>Technical Progress Report | 15 May, 1994 |
| | 6. |
| 7. Author(s)<br>Charles Annis | 8. Performing Organization Rept. No. |
| 9. Performing Organization Name and Address<br>United Technologies<br>Pratt & Whitney<br>P. O. Box 109600<br>West Palm Beach, FL 33410-9600 | 10. Project/Task/Work Unit No.<br>11. Contract(C) or Grant(G) No.<br>(C) N00014-91-C-0124<br>(G) |
| 12. Sponsoring Organization Name and Address<br>Office of Naval Research<br>Department of the Navy<br>800 N. Quincy Street<br>Arlington, VA 22217-5000 | 13. Type of Report & Period Covered<br>Quarterly<br>02/16/94 - 05/15/94 |
| | 14. |

15. Supplementary Notes

16. Abstract (Limit: 200 words)


This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences is the major goal of this project.


17. Document Analysis a. Descriptors

Fatigue, Fracture, Single Crystal, PWA 1480, PWA 1484

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

| 18. Availability Statement | 19. Security Class (This Report) | 21. No. of Pages |
|---|---|---|
| Unlimited | Unclassified | 11 |
| | 20. Security Class (This Page) | 22. Price |

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77)

* GPO : 1993 O - 381-526 (8393)